Use of Existing GPS Receivers as a Soil Moisture Network for Water Cycle Studies

Kristine M. Larson[1], Eric E. Small[2], Ethan Gutmann[2], John Braun[3], Andria Bilich[4], Valery Zavorotny[4]

(1) Aerospace Engineering Sciences, University of Colorado; (2) Geological Sciences, University of Colorado; (3) COSMIC-UCAR; (4) NOAA

Introduction

The global distribution and temporal variations of soil moisture are sought both for analyses and modeling purposes. Yet there is no existing global soil moisture dataset that fulfills the needs of the hydrology, climate, and ecology communities [*NRC*, 2007]. Soil moisture is measured *in situ* at many locations, both as part of individual studies or as part of monitoring networks. While these measurements are useful for small-scale or regional efforts, their utility for spatially-distributed studies is limited. Data gathered via satellite remote sensing provides consistent measurements of soil moisture at the global scale, but these data also have their difficulties. Errors are introduced because the pixel size of measurements is much larger (~10's km) than the scale over which soil moisture varies [*Njoku and Entekhabi,* 1996; *Njoku et al*., 2003]. Sampling may be infrequent (e.g., several days) compared to timescales of fluctuations. Vegetation and soil roughness complicate interpretation of the satellite signal. Future satellite missions are planned to minimize these problems. However, even new soil moisture satellites will require a global network of stations that provides comparable, *in situ* measurements of soil moisture to scale the magnitude of remote sensing estimates and to quantify the spatial and temporal variability that exists at scales finer than the satellite resolution [*Krajewski et al.*, 2006].

Here, we demonstrate that high-precision GPS receivers can be used to estimate fluctuations in near surface soil moisture. This is possible because GPS receivers gather energy from ground reflections in addition to the direct signal that travels between the GPS satellite and receiving antenna. The characteristics of the reflected signal change as soil moisture, and therefore the dielectric constant of the ground, varies. GPS-derived estimates shown here represent an average soil moisture value over an area of ~300 m^2, a much larger and more useful scale than typical *in situ* measurements. Given this sensitivity to soil moisture, some of the more than 5000 permanent and continuously operating GPS receivers that exist worldwide could be used to provide near-real time estimates of soil moisture for hydrology, climate, and ecology studies. Like the planned SMOS and SMAP missions, the GPS signals are L-band (1.57542 and 1.22760 GHz). Thus, GPS receivers are an optimal *in situ* data source to combine with future satellite measurements.

Project Description

For precise applications of GPS (e.g. plate boundary deformation, atmospheric water vapor, postglacial rebound, surveying), reflected signals are considered a source of error rather than a useful signal. Because of the complexity of the reflecting environment at most GPS sites (e.g. topography, buildings), there are no standardized modeling approaches for removing these effects. Instead, quantification of "multipath" levels is only used as a quality check on GPS sites, with high levels of multipath indicating a "bad site." GPS reflections have previously been proposed for use in soil moisture studies [*Martin-Neira*, 1993]. In those systems, a GPS receiver/antenna system specially designed to measure the reflected signal was flown on aircraft or in space [*Katzberg et al*. 2006]. In contrast, we examine the use of existing GPS instrumentation, designed to suppress reflections and installed on the Earth's surface for other purposes.

The equations describing GPS observations of reflections from the ground (or any horizontal planar reflector) have been known for many years [*Georgiadou and Kleusberg*, 1988]. The transmitted GPS signal arrives by both direct and reflected paths, with the receiver measuring the sum of these signals. The amplitude of the composite signal depends on a combination of ground surface qualities (dielectric constant; roughness) and the GPS antenna gain pattern. The phase relationship between the direct and reflected signals changes over time, modulating the observed signal amplitude.

The GPS site used in this study is located at Marshall, Colorado (Figure 1), ~10 meters from a NSF Earthscope site (http://www.earthscope.org). The vegetation type is short grass steppe. We used the six new Block IIR-M GPS satellites. Signals for these satellites reflect off the ground south of the antenna (Figure 2). For a known distance above the ground h and GPS wavelength □, the frequency f for multipath reflections is 4□h/□ [*Larson et al.*, 2008]. Least squares estimation is used to fit a sinusoid (amplitude A and phase offset □) to the GPS SNR data between elevation angles (E) of 10 and 30 degrees. Volumetric water content (VWC) was estimated in the soil using Campbell Scientific water content reflectometers (WCR) (Figure 3). These data were calibrated in the lab using soil from the site. Five probes were installed at 2.5cm and five at 7.5 cm depth, to measure VWC in the 0-5 cm and 5-10 cm depth range. Locations of the WCR probes relative to the GPS satellite tracks are shown in Figure 2.

Without a calibration for the antenna gain pattern, we do not have an absolute conversion between phase offset □ and VWC. Nevertheless, there is a very clear relationship between the two measures (Figure 3).

Fig. 1. GPS site at Marshall, Colorado.

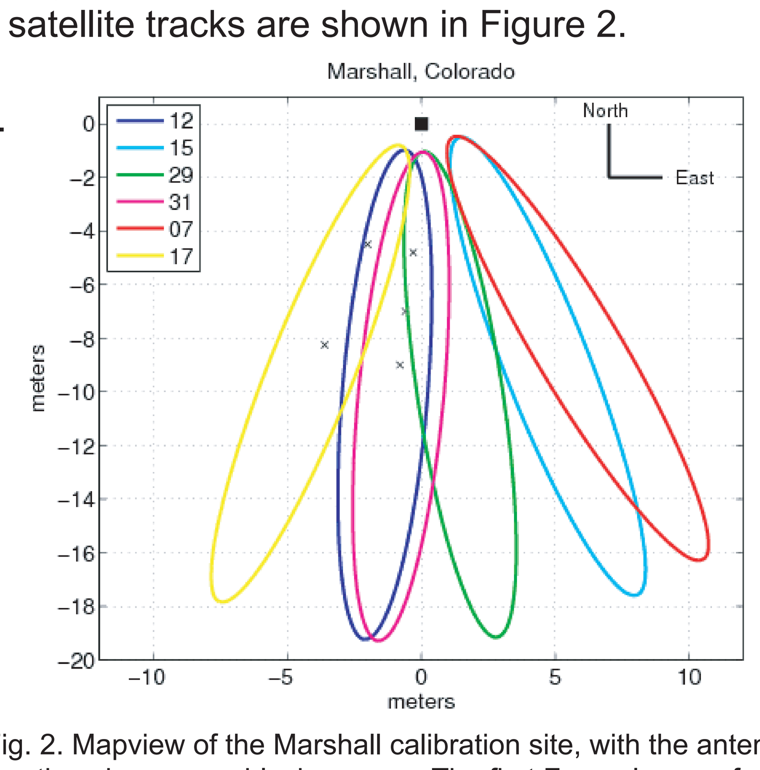


Fig. 2. Mapview of the Marshall calibration site, with the antenna location shown as a black square. The first Fresnel zones for the 6 GPS satellites used in this study are shown (for an elevation angle of 10 degrees). Location of the WCRs at 2.5 cm depth are shown as crosses.

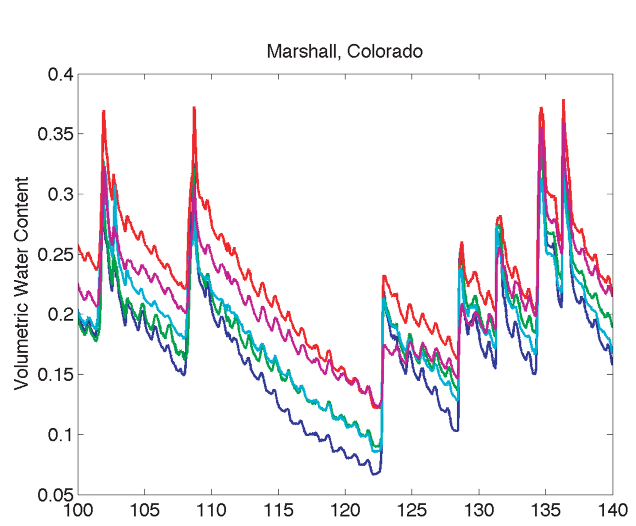


Fig. 3 Typical WCR measurements for probes buried at 2.5 cm depth.

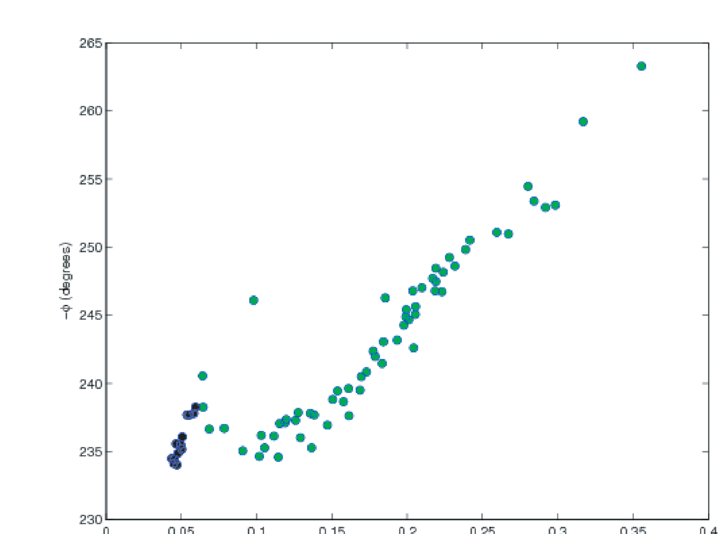


Fig. 4 . □ compared with VWC (defined by the average of five WCRs at a depth 2.5 cm). Dark circles indicate data beyond day of year 170.

Results

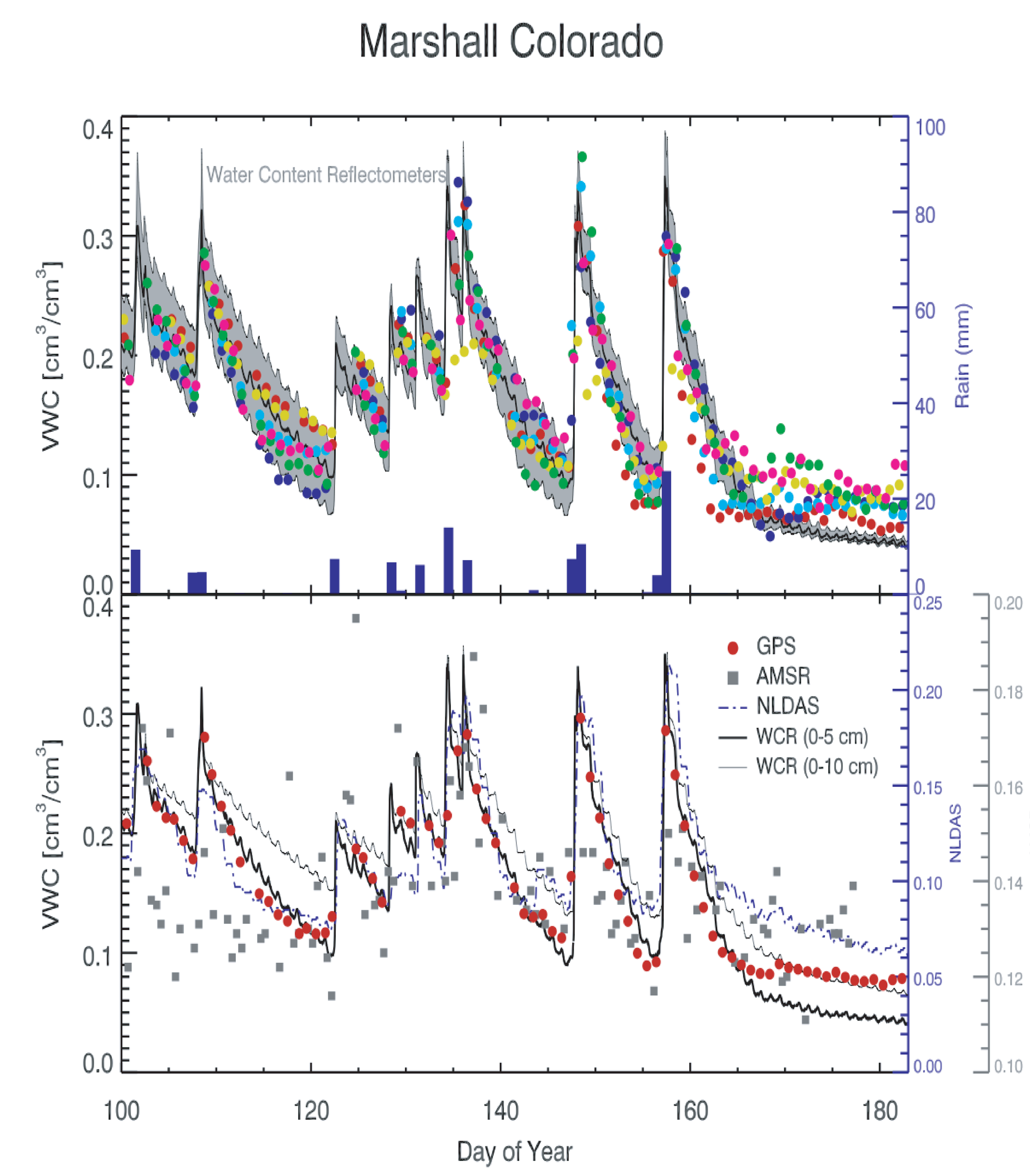


Figure 5.

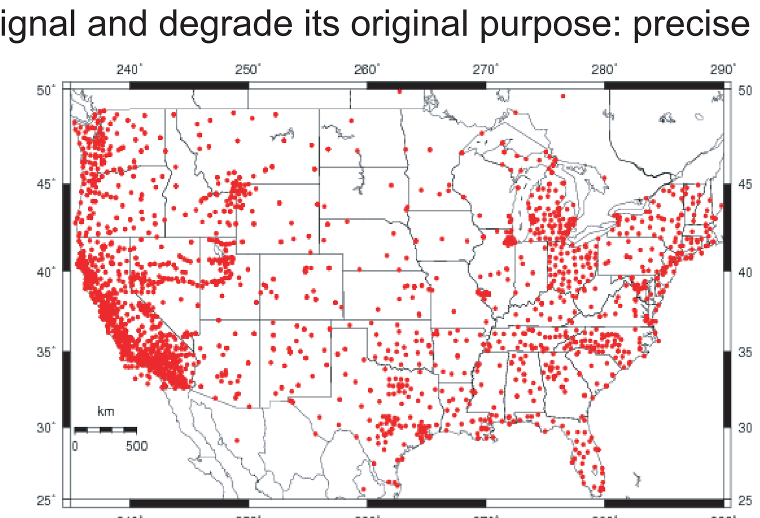
Top: variation in volumetric water content (VWC) from multiple GPS satellites (colors as in Figure 2) and WCRs. The range of the five WCRs is shown in grey and their mean is the black line.The daily precipitation totals are in blue. Bottom: VWC from four different sources, GPS (redcircles), AMSR (grey squares), NLDAS (blue dashed), WCR for 0-5cm depth (thick line), and WCR for 0-10cm depth (thin line). NLDAS and AMSR are on independent y-axes. GPS measurements are only shown on days when there was no snow and the daily average temperature was above 3 C.

Each GPS data point in Figure 5 is an average over the ~45 minutes that a given satellite is reflecting from the area of ground under study. Figure 5 demonstrates that the reflection parameter derived from the GPS data is highly correlated with the fluctuations in VWC_{0-5} measured by the WCRs. The correlation (r^2) between the individual satellite VWC values and mean WCR time series is 0.91. The GPS data matches both the timing and amount of drying very closely for each of the five major wetting-drying cycles recorded by the WCR probes. For example, in both datasets, the drying following the DoY 109 storm is slower and lesser in magnitude than that observed following the DoY 157 event. The mean GPS signal is not as tightly correlated with the mean of VWC_{5-10} (r^2 = 0.85), as the deeper soil moisture decreases more slowly than that recorded by the GPS. More details and discussion are available in *Larson et a*l. [submitted].

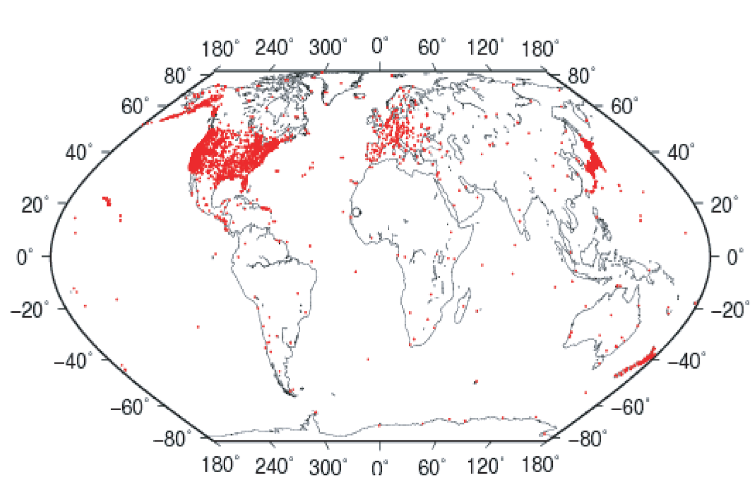
Existing GPS Receivers

Continuously operating high-precision GPS networks represent a new data source for the hydrologic and atmospheric communities. GPS data are freely available via anonymous ftp, often in real-time, but always within 24 hours. Site installation (reconnaissance, permitting), operations, and maintenance costs are already supported. In short, the data are free. Ultimately the value of these existing GPS networks for hydrology will depend on local site conditions and spatial density. The basic requirement for GPS soil moisture sites is that the antenna be located above relatively flat natural surface and away from urban structures. This is often the case for geophysical monitoring networks such as Earthscope. Survey networks, however are often deployed with antennas on buildings. Currently Japan, the US, and Europe have the largest GPS networks, producing publicly available data for more than 4000 receivers.

In the US, GPS receiver spacing varies from 50-150 km depending on the region. Nearly all the GPS receivers in the western US are supported by NSF and have uniform monumentation and instrumentation. The GPS receivers in the eastern US are primarily organized by NOAA and were typically installed to support surveyors and state and county transportation departments. Many of the eastern US sites cannot be used because the receivers are located on buildings. No existing GPS instrumentation is located beneath vegetation canopy, as this would obscure the direct signal and degrade its original purpose: precise geolocation.



GPS sites in the US with freely available data.



Global GPS sites with freely available data. Additional sites are available from Antarctica and Greenland.

Additional work is needed to evaluate the GPS soil moisture technique. Although vegetation at Marshall does not obscure the GPS signal, the effect of a range of vegetation structures needs to be evaluated, as is the case for all satellite-borne sensors. The impact of variations in GPS equipment (antennas and receivers) needs to be assessed. Finally, the technique should be tested for different soil types and surface roughness. There exists a large body of literature on retrieving soil moisture from L-band microwave radiometric observations [Wigneron et al., 2003]. This will guide the development of new retrieval algorithms for the GPS technique, including models that describe the dielectric properties of different types of soils and soil moisture profiles. We have recently expanded our analysis by installing two GPS sites near existing soil moisture sensors in Socorro, New Mexico. These sites have different precipitation patterns and vegegation types than Marshall.

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